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November 30, 1994

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William F. Caton, Acting Secretary
Federal Communications Commission
1919 M. Street, N.W., Rm 222
Washington, DC 20554

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FEDERAL COMMUNICATIONS COMMISSION
OFFICE OF SECRETARY

Re: PR Docket No. 93-61, Ex Parte
Automatic Vehicle Monitoring Systems

Dear Mr. Caton:

On September 15, 1994, David E. Hilliard, on behalf of Pinpoint Communications, Inc. ("Pinpoint") filed notice of an ex parte presentation in connection with the above-referenced proceeding. Included with that communication was a letter from Mr. Louis H. M. Jandrell (Vice President - Design and Development of Pinpoint) providing comments on an ex parte letter filed with the Commission by TIA on August 12, 1994. Attached is a response to Mr. Jandrell's comments. Please associate this material with the record of the above-referenced proceeding.

If there are any questions regarding this matter, please contact the undersigned.

Respectfully submitted,

Jay E. Padgett

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Telecommunications Industry Association

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Response to Pinpoint's Comments on "WIDE AREA PULSE-RANGING AVM/LMS: MESSAGING/LOCATING SYSTEM DESIGN TRADEOFFS AND PART 15 INTERFERENCE"

Dr. Jay E. Padgett
Chairman, TIA Consumer Radio Section
November 30, 1994

SUMMARY

Mr. Louis H. M. Jandrell has provided comments ("the Jandrell comments")[1] to the Commission on the paper "Wide Area Pulse-Ranging AVM/LMS: Messaging/Locating System Design Tradeoffs and Part 15 Interference" ("the AVM analysis")[2]. In his comments, Mr. Jandrell has misinterpreted some of the results and conclusions of the AVM analysis, and has provided some new calculations that lead to erroneous conclusions which then are used in an attempt to refute some of the key points in the AVM analysis. Moreover, in several instances it appears from Mr. Jandrell's comments that he either did not fully understand some of the calculations in the analysis, or chose to ignore them in the interest of maintaining Pinpoint's previously-stated positions. Those shortcomings of the Jandrell comments are addressed herein.

In sum, the major conclusions of the AVM analysis stand: (1) reverse-link bandwidths of 8 to 16 MHz may provide better ranging accuracy in the presence of multipath than lower bandwidths (*e.g.,* 4 MHz), but there is no *capacity* benefit, in terms of the locating function, to increasing the bandwidth to 8 or 16 MHz compared to 4 MHz;

1. Louis H. M. Jandrell, Vice President - Design and Development, Pinpoint Communications, Inc. ("Pinpoint"), in a letter to Mr. William F. Caton, Acting Secretary, Federal Communications Commission, September 15, 1994.
2. Dated August 8, 1994, by J. E. Padgett, filed as an attachment to an August 12, 1994 *ex parte* presentation in association with PR Docket 93-61 by the Telecommunications Industry Association ("TIA") and also as an attachment to a joint *ex parte* filing by a number of Part 15 interests, under a cover letter from Mr. Henry M. Rivera, on August 12, 1994. "AVM" and "LMS" stand for "Automatic Vehicle Monitoring" and "Location and Monitoring Services," respectively.

and (2) wideband forward links should not be authorized because they are not spectrum-efficient and pose an unnecessary interference threat to other users of the band. Indeed, it is clear from the calculations provided by Mr. Jandrell in his comments that the entire forward link throughput requirement of Pinpoint's current system design concept, for both the polling and messaging functions, could be met with a single non-spread spectrum forward link with a bandwidth of about 500 kHz. This narrowband forward link would be shared among base stations on a time-division basis, as is the wideband forward link in Pinpoint's concept, and would provide the same functionality as the wideband forward link. It would be much less likely to suffer interference than the wideband forward link, and would greatly reduce the potential for interference to other users of the band, compared to the wideband spread spectrum approach. Unfortunately, Mr. Jandrell does not seem to have considered this alternative in his comments, but rather postulates several sub-optimal narrowband solutions in an attempt to defend the need for a wideband forward link.

Mr. Jandrell also takes issue with the calculations given in the AVM analysis of the potential for the wideband forward link (WFL) to interfere with other systems operating in the band. For example, he provides a calculation which suggests that a cordless telephone would typically receive interference from only a single Pinpoint base station, and therefore would suffer interference only 1% of the time, based on the average duty cycle for forward link transmissions from the interfering base. As shown here, this 1% figure is quite misleading, and does not accurately represent the actual effect of the forward link interference on the victim device. Although a given base may be transmitting only 1% of the time on average, the transmissions consist of short (about 200 μs) bursts randomly distributed in time. Even with a low average duty cycle, these bursts can be extremely disruptive to a cordless telephone. Moreover, if the base station is operating in the messaging mode (as opposed to the polling mode), or there is a high traffic density near the base, the duty cycle can be considerably higher than 1%. The effect on the performance and capacity of both direct sequence and frequency hopping cordless telephones is discussed herein, and the Attachment provides a detailed analysis of the effect of the wideband forward link transmissions on frequency hopping cordless telephones (which is the more complicated of the two cases).

In an attempt to demonstrate that Pinpoint's wideband forward link will not cause harmful interference to cordless telephones operating in the 902-928 MHz band, Mr. Jandrell summarizes a test conducted by Pinpoint with a "frequency hopping" cordless telephone. From Mr. Jandrell's description of the experiment, it seems likely that the cordless telephone was in fact not a frequency hopping unit, but perhaps a direct-sequence unit with frequency agility. In addition to this possible misrepresentation of the equipment under test, the experiment was flawed in that the forward link transmission format used by Pinpoint was more benign than the "bursty" polling transmission that would typify actual locating operations. Notwithstanding these shortcomings, there seems to be one useful piece of data from the experiment: when the cordless phone was forced to operate within the Pinpoint forward link bandwidth, the non-degraded range (within an office building) was reduced from 250 feet to 50 feet.

Finally, Mr. Jandrell raises the contention that the interference suffered by Part 15 devices from a Metricom-type wireless packet data system will be more problematic than interference from an AVM system such as Pinpoint's. Such a comparison was not made in the AVM analysis and is beyond the scope of this response (and in fact is irrelevant to this proceeding, which is concerned with FCC Rules for AVM/LMS, not Part 15). Although Mr. Jandrell's comparison of interference from Metricom's system with that from Pinpoint's system appears simplistic (for one thing, it does not account for timing effects), a detailed analysis of that particular point is perhaps best undertaken by Metricom.

Even considering all of Mr. Jandrell's arguments, the main points regarding wideband forward links that should be considered by the Commission in making its decisions in this proceeding remain:

- Pinpoint's wideband forward link poses a significant interference threat to other devices using the 902-928 MHz band, including cordless telephones.
- It is not necessary for Pinpoint to use a wideband forward link; the system functionality envisioned by Pinpoint could be achieved using 500 kHz of bandwidth for the forward link.
- A wideband forward link is less efficient from the perspectives of power and spectrum utilization, and more likely to sustain interference from other users of the band than a narrowband (non-spread spectrum) forward link.

REVERSE-LINK BANDWIDTH AND CAPACITY

In section II, the AVM analysis discusses the relationship between the bandwidth of the reverse-link signal and the ranging accuracy of the receivers used by wideband pulse-ranging systems to estimate the time-of-arrival (TOA) differences in signals at multiple base stations. These TOA differences are used to estimate the location of the reverse-link transmitter (in the vehicle) using hyperbolic multilateration (HML). The dominant source of error in the location estimate is error in the receiver TOA estimate. Characterization of the TOA estimation error therefore is necessary for analysis of HML AVM system performance. At this point, terminology needs to be clarified. In the AVM analysis, the term *ranging error* denotes the error in the estimate of a receiver of the distance of the vehicle from that receiver. The ranging error in feet is essentially equal to the TOA estimation error in nanoseconds. Mr. Jandrell uses the term "ranging error" to represent the error in the actual position of the vehicle (calculated by the central intelligence of the system from the differences in the TOA estimates from multiple receivers), which is referred to here as the "locating error." It appears that Mr. Jandrell has misinterpreted the use of the term "ranging error" in the AVM analysis.

The main conclusions derived from the material in section II of the AVM analysis are:

1. The TOA estimation error (and therefore the ranging error) is dominated by multipath rather than what Mr. Jandrell refers to as "noise-induced timing uncertainties," [3] even when the receiver is operating near its threshold (minimum carrier-to-noise or carrier-to-interference ratio). The relationship between bandwidth and multipath-induced error used in the AVM analysis was based on information supplied by Pinpoint in an *ex parte* communication.[4]

2. While the bandwidth determines the TOA estimation error, and therefore the ranging error, it does not determine capacity.

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3. Jandrell comments at p. 5.
4. Louis H. M. Jandrell, *ex parte* letter filed May 11, 1994 in association with PR Docket 93-61. See footnote on p. 8 of the AVM analysis.

3. Due to the relationship between bandwidth and multipath-induced error, it appears that bandwidths in the range 8 to 16 MHz may be justified for the AVM reverse link, to provide improved locating accuracy.

Based on this third point, it was stated in the AVM analysis that: "The availability of a relatively large block of spectrum (perhaps 8 to 16 MHz) for the reverse link may be justified on the basis of locating accuracy in the presence of multipath, with limits on the mobile transmit power and duty cycle." [5] Given this conclusion, clearly stated up front, in the Executive Summary of the AVM analysis, it is difficult to understand why Mr. Jandrell has taken issue with this point, since it seems to be in agreement with Pinpoint's design philosophy. It appears that he may have misunderstood the analysis and conclusions; in his own conclusions he misrepresents the conclusions in the AVM analysis stating: "At bottom [Dr. Padgett's] recommendations **that no more than 4 MHz** he [*sic*] allocated for individual wide-area AVM systems and that wideband forward links be prohibited are misguided" [6] [emphasis added]. Indeed, one of the subsections of the Jandrell comments is entitled "Use of a Bandwidth of at Least 8 MHz," [7] and discusses for several pages essentially those same factors discussed in section II of the AVM analysis. On this point, at least, it appears that Mr. Jandrell is in "violent agreement" with the AVM analysis.

Regarding the alleged increase in capacity with bandwidth, the Jandrell comments make two contradictory claims. Mr. Jandrell first discusses (correctly) the dominance of the multipath-induced error over the noise-induced error as noted above in point (1), then proceeds to invoke the familiar Cramer-Rao bound argument to support the claim that capacity increases as the bandwidth squared (the Cramer-Rao bound is based on noise-induced error and does not account for multipath-induced error). Indeed, regardless of the presence of multipath, the carrier-to-noise ratio must still exceed the receiver threshold for proper operation (as acknowledged on p. 7 of the Jandrell comments). This is precisely the point made in the AVM analysis, which showed that given the dominance of the multipath-induced error and the need to

5. Executive summary of the AVM analysis at p. iii. See also the conclusions of the AVM analysis at p. 38.
6. Jandrell comments at p. 23.
7. Jandrell comments at p. 3.

maintain the receiver carrier-to-noise ratio above threshold, bandwidth and capacity are not related, for reverse link bandwidths of interest in this proceeding (*i.e.* 4 MHz or more).[8] Unfortunately, Mr. Jandrell does not address the related material in the AVM analysis quantitatively, and it is unclear whether he completely understood it. He merely restates the claim made repeatedly by Pinpoint and other AVM interests in this proceeding that based on the Cramer-Rao bound, capacity increases as the square of the bandwidth.[9]

WIDEBAND FORWARD LINKS

The AVM analysis concludes that wideband forward links should not be implemented in AVM systems because (1) they are unnecessary to support the functionality of the AVM system, and are in fact less efficient from a spectrum/power utilization perspective than narrowband forward links, and (2) they pose an unnecessary interference threat to other users of the band. Mr. Jandrell takes issue with both of these points.

Spectrum Requirements for the Narrowband Approach

The AVM analysis suggests that instead of a wideband spread-spectrum forward link, a narrowband (*i.e.*, non-spread spectrum) approach could be used to provide the required forward link capacity. Mr. Jandrell argues that this is impractical, attempting to prove his point by concocting several sub-optimal system solutions based on the narrowband approach. As summarized below, his arguments do not withstand detailed scrutiny.

Consider the parameters for the Pinpoint system cited by Mr. Jandrell: 1500 locations/sec and 6 bytes per location, for a total forward-link throughput requirement of 72 kb/s.[10] Mr. Jandrell then states that the use of narrowband forward links would require an additional two bytes per message for the assignment of a response time,

8. See AVM analysis at pp. 4-10.
9. Jandrell comments at pp. 7-8.
10. Jandrell comments at p. 13.

giving a total required throughput of 96 kb/s. He further explains that alternatively, Pinpoint's systems can perform 500 locations/sec, 85 of which include 2.4 kbit messages, and shows that this equates to a total throughput of roughly 240 kb/s.[11]

In Pinpoint's current design concept, these forward link throughput requirements are met with a single wideband spread spectrum forward link with a 300 kb/s rate,[12] which is time-shared among a large number (*e.g.*, 30 to 35) base stations. This time-division approach allows the capacity of the forward link to be adaptively concentrated where it is needed at any particular time. On average, each base station uses the forward link about 3% of the time. In the polling mode, the base station actually transmits during about 30% of the polling cycle, so the average forward link transmit duty factor per base is about 1% in the polling mode. The system wide throughput is 0.30×300 kb/s = 90 kb/s, which is consistent with the 72 kb/s net throughput requirement. In the messaging mode, the forward link transmit duty cycle obviously is higher.

Mr. Jandrell states that with a narrowband (non-spread spectrum) approach and a net modulation efficiency of 0.5 kb/s per Hz,[13] the forward link bandwidth requirements for the polling and messaging functions would be 192 kHz and 480 kHz, respectively. In other words, the entire forward link throughput requirement could be accommodated in a bandwidth of 480 kHz. This allows for both the polling and messaging functions, and includes the additional two bytes per message for response time assignment. Up to this point, Mr. Jandrell's analysis appears reasonable. However, he then states that this bandwidth requirement must be multiplied sevenfold to allow for the assignment of separate forward link frequencies to each cell in a seven-cell cluster,[14] resulting in a total spectrum requirement of about 3.4 MHz. This would equip each cell with enough paging capacity for the entire system, on a continuous basis. It is unclear why this would be necessary, since a single 240 kb/s forward link could be shared among all the base stations on a time division basis in much the same manner as the wideband forward link is shared in Pinpoint's current design concept. The time-sharing of a single non-spread forward link seems to be the

11. Jandrell at p. 14.
12. In some cases, Pinpoint has cited a 360 kb/s capacity.
13. Jandrell comments at pp. 13-14.
14. Jandrell comments at p. 14.

most obvious alternative to a time-shared wideband spread spectrum forward link, and would have the least impact on Pinpoint's system architecture. However, Mr. Jandrell does not even mention it as an alternative. Rather, he postulates several sub-optimal narrowband forward link system solutions in an attempt to discredit the concept of using a narrowband forward link.

The Lower Spectrum Efficiency of Wideband Forward Links

Section V of the AVM analysis demonstrated that wideband forward links are less spectrum- and power-efficient than narrowband forward links.[19] The only statement that Mr. Jandrell makes regarding that conclusion is:

> Dr. Padgett argues that a wideband forward link is more likely to suffer interference than a narrowband forward link. While theoretically this is true, when selecting its system design, Pinpoint considered this among a number of factors such as the processing gain associated with a wider bandwidth and the minimum amount of ground level interference that the system would experience. Pinpoint also considered the statistical nature of potentially interfering sources, which requires a congruence of spatial, temporal, and frequency considerations in order for interference to occur. See discussion of Pinpoint Reply Comments March 29, 1994, at pp. 29-30.[20]

Unfortunately, this is not very illuminating and gives no clue as to what analyses Pinpoint may or may not have conducted in the process of designing its system. The referenced Reply Comments are no more enlightening, and merely make the same sort of general statements, without any quantitative support.

It should be clear from even a moderately careful reading of section V of the AVM analysis that the statistical nature of the interference problem and the associated space, time, and frequency factors have all been taken into account. Moreover, that analysis gives a *relative* comparison of narrowband and wideband forward links, and does not depend upon the assumption of a specific Part 15 device density for the results. Since this material related to one of the major points of the AVM analysis, Mr. Jandrell's relative silence on the issue suggests that either he did not carefully

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19. See AVM analysis at pp. 25-33, and the Appendix.
20. Jandrell comments at p. 20, footnote 28.

review the material or that he deliberately chose not to address it for lack of a reasonable basis for doing so.

Interference From Wideband Forward Links

Mr. Jandrell also takes exception to the point raised in the AVM analysis that a wideband, high-power forward link will constitute an interference threat to other users of the band.[21] He notes that the forward link transmit power will be 500 watts ERP rather than the 5 kW assumed in the AVM analysis, and that the antenna height will be 200 feet rather than the 300 feet used in the AVM analysis for the example calculations.[22] On the basis of these new parameters, and the average forward link duty cycle, Mr. Jandrell revises the interference calculation to argue that the interference is less than suggested by the examples in the AVM analysis:

> the reduced effective range of the wideband forward link results in the noise floor being raised to -95 dBm only 5.4% of the time in a 100 kHz bandwidth throughout an 8 MHz sub-band at a receiver 30 feet above ground level. At 6 feet above ground level, the Pinpoint occupancy of the 8 MHz band is down to 1%.[23]

These calculations were based on the number of Pinpoint base stations within the "radius of interference" necessary to raise the noise floor of the victim receiver to the indicated level. It should be noted that the percentages cited are based on the *average* forward link duty cycle (about 1%) cited by Mr. Jandrell. If traffic peaking is as severe as Mr. Jandrell indicates in his analysis of the bandwidth required for narrowband forward links (*i.e.*, if much of the system's capacity may at times be concentrated in a single cell), the percentages could be much higher in some locations at some times. Further, base stations using the forward link for messaging will be operating with a higher transmit duty cycle.

Timing Factors

On the surface, these figures suggest that the interference will be fairly light, but a

21. See pp. 34-35 of the AVM analysis.
22. Jandrell comments at p. 16.
23. *Id.*

more detailed examination shows that these low average percentages are misleading in terms of the effect of the interference on the victim devices. To see this, Pinpoint's system timing must be considered. Pinpoint's frame format is based on a sequence of slots 640 μs in duration. In the polling (interrogation) mode, the forward link transmits during roughly the first 200 μs of a slot. The remainder of the slot is used for guard time and the response of the mobile unit. Slots are randomly assigned to base stations depending on the locations of the vehicles to be polled. Typically, a given base will use about 3% of the slots on average (the slot usage of a given base may be higher or lower depending on the traffic demand in the area of that base). In a 1-second time segment, there are 1500 slots available for polling; the remainder of the time is used for system overhead. Thus, a base station operating with the 3% average slot utilization factor will use 45 slots/second, randomly distributed in time.

It is interesting to consider the relationship between the timing of Pinpoint's forward link and that of a Part 15 device such as a cordless telephone or a wireless data system. Such devices will typically have frame durations of 5 milliseconds or more. As an example, consider a 10 millisecond frame, which overlaps 16 Pinpoint slots ($10 \div 0.64 = 15.6$). Figure 1 illustrates the basic timing relationships.

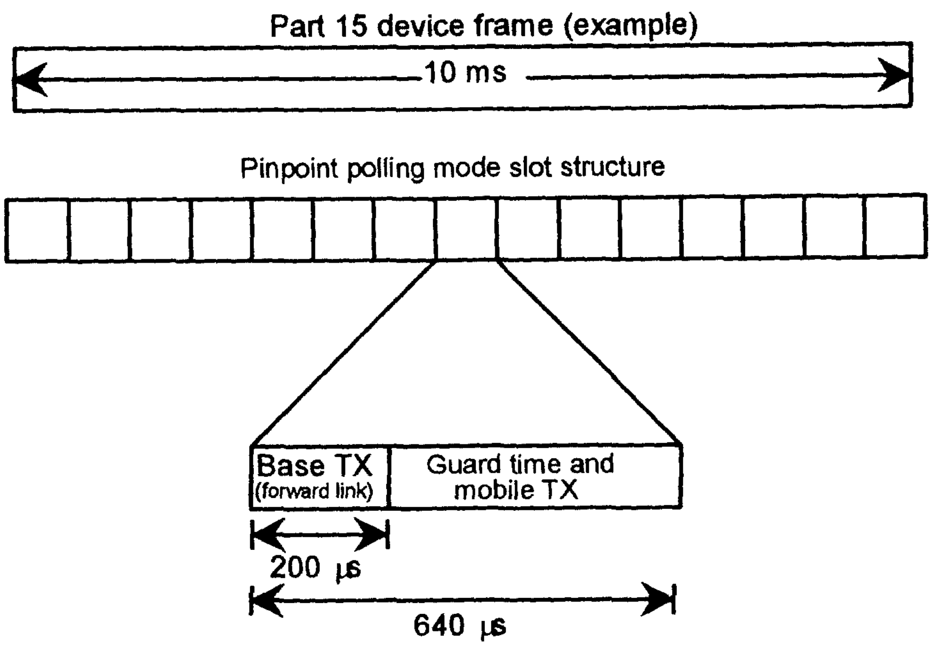

Figure 1. *Relationship of a 10 ms Part 15 frame to the Pinpoint polling mode slot structure.*

If the Part 15 device is within interfering range of a single Pinpoint base station, and the base station is operating with the average 3% forward link slot utilization factor, then the probability that any given slot is *not* active is 97%, or 0.97. The probability that *none* of the 16 overlapping slots are active therefore is $0.97^{16} = 0.614$, so there is a 38.6% probability that at least one slot will be active and will cause a "hit" to the 10 ms frame. On the average, of course, there will be 45 hits/s, assuming the victim device is within the passband of the Pinpoint forward link. This simple example shows that even with a single interfering base station operating at a 3% slot utilization factor (a 1% transmit duty factor), interference from Pinpoint's forward link can by no means be dismissed as harmless.

The actual effect of the interference will depend on the nature of the victim system. Wireless data systems typically manage errors using error detection such as a CRC (Cyclic Redundancy Check) with ARQ (Automatic Repeat reQuest). If the CRC fails (indicating that there are bit errors), the frame or packet is retransmitted. Thus, chronic "bursty" interference would be expected to reduce the system throughput.

For a voice-based system such as a cordless telephone, the effect would be different. The cordless telephone frame consists of a block of speech bits plus some control bits for signaling, security, and interference detection. Most of the frame is used for the speech bits, which are *not* specifically protected with error detection. However, the control bits *are* protected with error detection, and if errors in the control bits are detected, the cordless telephone typically will "mute" the frame. The implicit assumption is that if there are errors in the control bits, there probably are errors in the speech bits as well. The muting protects the user from the (unpredictable) output of the speech coded driven by an errored bit sequence ("pops," "clicks," etc.). In addition, if control bit errors are detected on several frames, the control algorithm of the cordless telephone may elect to seek another channel. Again, the implicit assumption is that interference has developed on the existing channel.

These strategies for coping with interference work well when the duration of the interference is on the order of a frame or longer. However, the short random interference bursts from the Pinpoint forward link raise the possibility that "hits" will occur on speech bits but not on control bits. In fact, because the speech bits account for a much larger percentage of the frame than the control bits, speech bits are more likely to be hit. When a speech bit hit occurs without a control bit hit, the cordless telephone will not "know" that it has received interference. The frame will not be muted and the interference-avoidance mechanism will not be triggered. As a result, the user will hear the hits but the cordless telephone may not adapt, or may adapt too slowly.

Beyond these general observations, the exact reaction of a victim device to the Pinpoint WFL interference will depend on the design details of the device (the frame duration, the specific interference-avoidance strategy, the channel bandwidth, etc.) as well as the bandwidth of the Pinpoint WFL and the actual slot utilization factor of the interfering base station.

Effect of WFL Transmissions on Cordless Telephones

It is instructive to compare the effect on cordless telephone designs using the two spread spectrum techniques that Part 15 devices are allowed to use in the 902-928 MHz band: direct sequence spreading and frequency hopping. It will be assumed that in each case, the cordless telephone is equipped with the appropriate interference avoidance strategy. In the direct sequence case, the cordless phone is assumed to have access to M frequency channels, each sufficiently wide to accommodate the data rate multiplied by the spreading factor (a minimum of 10). The cordless telephone is assumed to remain on a channel until control bit errors are detected, then move to another channel. If the WFL bandwidth is B_{FL} (MHz), the effect of the WFL is to reduce the available number of clear channels to $M(1 - B_{FL}/26)$. For example, if $B_{FL} = 16$ MHz and $M = 26$, then the number of clear channels is 10. This represents a capacity reduction of more than 60%.

It may, however, take the cordless telephone quite some time to move to a clear channel, due to the bursty nature of the WFL transmissions. Good design practice for the radio environment suggests that the cordless phone should detect interference on multiple frames within a short time (*e.g.*, two or three consecutive frames) to trigger a frequency change. This is to avoid over-reacting to transient effects such as deep momentary multipath fades, such as can be caused by a passing vehicle, for example. In the case of bursty WFL interference, however, the multiple-hit requirement greatly reduces the probability that the WFL will trigger a frequency change. For example, assume there are two control-bit fields (one for the base-to-handset link and one for the reverse link), and the WFL is operating with a 3% slot utilization factor. The probability that neither control bit field is hit is $0.97^2 = 0.94$, so the probability of a control field hit is 6%. Hence, the probability of control field hits on a given pair of sequential frames is $0.06^2 = 0.0036$, or 0.36%. The cordless phone therefore may remain on the interfered channel for quite some time before moving, and even after it moves there is no guarantee that the new channel will be interference-free. In fact, with a 16 MHz WFL, the odds are against it. Meanwhile, the cordless phone user is experiencing 45 hits per second (from a Pinpoint base station with the 3% average slot utilization factor).

For a frequency hopping cordless telephone, the analogous interference-avoidance mechanism is "Dynamic Frequency Replacement" (DFR). This provides a way of adapting to interference that is consistent with the FCC requirement that a hopping pattern must include at least 50 distinct, randomly-selected frequencies. With DFR, when interference is detected on one of the frequencies, that frequency is replaced with a different randomly-selected frequency (which also must be different from all other frequencies in the hopping pattern). The capacity analysis for frequency hopping with DFR is more complicated than for the direct sequence case, and is provided in detail in the Attachment. However, the net result is qualitatively similar to that for the direct sequence case in some ways; undetected hits causing noticeable impairments to the speech quality continue more or less indefinitely, depending on the exact details of the triggering requirement for frequency replacement.

One obvious way to make hits more "detectable" by the Part 15 devices is to aggregate the WFL transmissions on each base, so that a Pinpoint base station transmits on multiple sequential slots. This will increase the probability of a control field hit and speed up the process of changing channels (in the direct sequence case) or replacing frequencies (in the frequency hopping case). A high activity factor for an interfering base would have a similar effect. At best, however, capacity (roughly proportional to available spectrum) is reduced by the ratio of the WFL bandwidth to the total available bandwidth (26 MHz in this case).

Although the exact effect of WFL interference to Part 15 devices obviously depends on the design details of the individual Part 15 devices, the overall conclusion is clear: the use of wideband forward links will have a noticeable impact on the operation of many types of Part 15 devices, including cordless telephones and wireless packet data systems. This problem could be avoided by the use of a narrowband (non-spread spectrum) forward link, without impacting the functionality or capacity of the AVM/LMS system. Thus, the use of a wideband forward link is inappropriate in a shared band such as 902-928 MHz, and represents a waste of valuable spectrum that otherwise could be shared among a number of diverse products and services.

Pinpoint's Cordless Telephone Interference Test

The Jandrell comments describe a test that was conducted by Pinpoint to determine the effect of the Pinpoint forward link on a "Part 15 frequency hopping cordless phone" [24] which was operated in an office building about 300 feet (line of sight) from a Pinpoint transmitter using a power of 100 W ERP.[25] To test the effect of the Pinpoint transmitter on the range of the cordless phone under "worst-case" conditions, the cordless phone base station was placed next to the window across from the Pinpoint base station. When forced to operate on the frequencies used by the Pinpoint base station, the range of the cordless telephone for non-degraded reception was reported to have decreased from about 250 feet to 50 feet. Clearly, a five-fold range reduction will be unacceptable to many users who purchase wireless business communication systems precisely to achieve a range of several hundred feet.

It was also noted in the Jandrell comments that moving the base unit away from the window by 30 feet resulted in a 20 dB reduction of the interfering signal.[26] In connection with this, Mr. Jandrell states that "The non-degraded range would be expected to show a corresponding increase."[27] The range does not appear to have been determined with the reduced interference power, or if it was, the results are not reported in the Jandrell comments.

Mr. Jandrell makes the point that to conduct this test, "the Part 15 phone had to be fooled into staying in the channel in which Pinpoint's station transmitted,"[28] but does not explain how this was accomplished, and absent further explanation, the statement is somewhat puzzling. Without reverse-engineering the cordless phone and modifying the internal control structure (which might not even be practical, depending on the internal architecture of the device and the extent to which the control functions are embedded in integrated circuits), the only way to force an adaptive frequency-hopper to operate on specific frequencies would be to "jam" the other frequencies. The lack of details regarding this part of the experiment, and the lack of any identification of

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24. Jandrell comments at p. 20.
25. Jandrell comments at pp. 20-21 and the figure entitled "Set-up For Cordless Phone Test."
26. Jandrell comments at p. 21.
27. *Id.*
28. *Id.*

the cordless telephone model used, raise questions about whether the unit tested actually was a frequency hopper (most §15.247 cordless telephones currently on the market use direct sequence spreading rather than frequency hopping). It seems possible that Mr. Jandrell misunderstood the nature of the product being tested, and that it was actually a direct-sequence phone with multiple channels and frequency agility, as described above. The fact that without being "fooled" into staying within Pinpoint's band, the phone automatically moved away from the forward link transmissions is explained by Mr. Jandrell's description of the forward link transmission format used in the test:

> The base station ERP was 100 W for the test rather than the expected 500 W ERP in a deployed network. In order to compensate partially for this, the airtime usage was increased to 7% from the expected average of 0.9%. In addition, the test transmitter sent a 2.7 ms burst, typical of a message containing 750 bits of user data rather than a location poll, which is only a few hundred microseconds in length. This provided a nearly worst case scenario for the test.[29]

In light of the previous discussion about the effect of the short bursty nature of Pinpoint's location polling transmissions, it is clear that the test scenario was in fact not worst-case at all. Rather, the relatively long forward link bursts used in the test allowed the cordless telephone to sense the interference and initiate a frequency change. In addition, the lower ERP used in the test suggests that the test results are somewhat optimistic with respect to the range reduction that would be caused by an actual forward link under similar circumstances.

Considering these flaws in Pinpoint's test, it is evident that the only valid conclusion from the test is that Pinpoint's wideband forward link can cause severe reduction in the operating range of cordless telephones in the 902-928 MHz band.

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29. Jandrell comments, pp. 20-21, footnote 29.

CONCLUSION

In his comments, Mr. Jandrell has attempted to discredit the AVM analysis because certain of its conclusions are at variance with some of the claims made by Pinpoint in the record of PR Docket 93-61. However, Mr. Jandrell misrepresents the AVM analysis on one point, ignores it on others, and uses a flawed set of assumptions and the resulting erroneous conclusions in an attempt to refute it on still another. He has presented no good arguments for reconsidering the main conclusions and recommendations of the AVM analysis as they pertain to an AVM band plan and the appropriate FCC rules to govern AVM/LMS operation: (1) wideband forward links should not be allowed, because they are unnecessary (the same functionality could be achieved with a narrowband approach) and pose a significant interference threat to other users of the band; and (2) while relatively wide reverse-link bandwidths (8 to 16 MHz) may provide improved ranging accuracy in the presence of multipath, these bandwidths offer no capacity increase over a 4 MHz bandwidth.

ATTACHMENT

COLLISION ANALYSIS FOR FREQUENCY HOPPING CORDLESS TELEPHONES WITH ADAPTIVE HOPPING SEQUENCES

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ABSTRACT

Part 15 of the FCC Rules allows unlicensed frequency hopping and direct sequence devices to operate in three of the ISM (Industrial, Scientific, and Medical) bands. With frequency hopping, a "collision" occurs whenever two or more devices in close proximity occupy the same frequency simultaneously. This paper provides a collision analysis for a group of cordless telephones that use frequency hopping and are operating in close proximity. Propagation path loss is ignored; it is assumed that when two units occupy the same frequency simultaneously, both experience a collision. It is also assumed that all units hop at the same rate, but hop sequences are randomly-selected and the hoppers are not necessarily hop-synchronized. A collision-sense/dynamic frequency replacement (CS/DFR) discipline is assumed to be used; that is, when a unit experiences a collision on a given hop, it adapts by selecting at random a new frequency for that hop in a subsequent cycle of the hopping sequence. A mathematical model is developed which, given the number of units operating simultaneously and the number of available frequencies, allows the collision probability to be calculated recursively. Analytic results based on the mathematical model are compared to simulation results. The model is then extended to include the effect of a wideband, high-power forward link (base-to-mobile channel) for AVM/LMS (Automatic Vehicle Monitoring/Location and Monitoring Services) applications.

The analysis and simulation results indicate that without the wideband forward link, a relatively large number of cordless telephones (more than forty for the unsynchronized case and more than eighty for the synchronized case) can operate in close proximity and very rapidly converge to a collision-free state. However, if the wideband forward link is introduced, the performance of the cordless telephones is significantly degraded, even with a relatively small number of units (e.g., six), whether or not the hoppers are synchronized.

I. INTRODUCTION

A. Background

Part 15 of the FCC Rules, which governs the operation of unlicensed RF devices, includes provisions for use of some of the ISM (Industrial, Scientific, and Medical) bands by unlicensed devices using frequency hopping or direct sequence spread-spectrum modulation. For the 915 MHz ISM band (902-928 MHz), the requirements for frequency-hopped operation specify that (1) at least 50 randomly-selected frequencies must be used, (2) the bandwidth of each frequency channel cannot exceed 500 kHz, (3) the hop duration must be 400 ms or less, and (4) the frequencies in the repertoire must be randomly-selected and all of them must be used equally.

The objective of this analysis is to understand the behavior of a group of such devices that are close enough together to interfere with one another (e.g., within the same room). In that case, when two units attempt to occupy the same frequency in the same timeslot, both suffer a "collision" (or a "hit"); propagation path attenuation, which allows two units[1] sufficiently separated in distance to successfully use the same frequency simultaneously, is ignored. Each unit is assumed to react to the collision by replacing the affected frequency in its hop sequence by another randomly-selected frequency. This discipline will be called "collision-sense/dynamic frequency replacement" (CS/DFR). The purpose of this analysis is to determine the relationship between the number of frequencies available and the system capacity; that is, the number of users within interfering range of each other that can operate simultaneously and converge to a collision-free state using CS/DFR.

B. Assumptions

For purposes of this analysis, the following assumptions are made:

- The hopping pattern consists of the same number of hops for each unit. One cycle of the hopping pattern is called a "superframe" (SF).
- Although all units hop at the same rate, there is no hop-synchronization among them; they all change frequencies at times that are random with respect to one another.
- The frequencies for each unit's initial hopping pattern are chosen randomly.

1. A "unit" refers to a base-remote pair.

- If a unit is hit on a given hop on SF i, it will randomly choose a frequency to use on that hop in SF $i+1$ (later this assumption will be modified slightly to require multiple hits on successive superframes to trigger a frequency replacement). This allows the possibility that after experiencing a collision a unit may choose to use the same frequency again. For all hops that are "clear" (not hit) on SF i, the unit uses the same frequency for those hops in the next SF.
- Adjacent-frequency interference is ignored.
- The number of available channels is at least several times larger than the number required in the hopping sequence.

Note that the assumptions of random frequency selection (both initially and after a hit) allow the possibility that a unit could use the same frequency twice in a superframe. This will not be the case in actual operation; for compliance with the FCC Rules, a unit is constrained to use a given frequency on no more than one hop per superframe. However, it is expected that the effect of this simplifying assumption on the collision statistics of interest here will be slight (this will be verified later by comparison of the analytic results to those from a simulation).

II. MATHEMATICAL MODEL

A. Overview

In this section, a mathematical model is developed to describe the situation outlined above; namely, a group of frequency-hopped cordless telephones are all within interfering range of one another (e.g., all within a single room), so propagation effects and spatial distributions are not considered. Intuitively, one would expect that with CS/DFR, if the ratio of the number of frequencies to the number of users is sufficiently high, the situation might eventually evolve to a collision-free state.

The objective of the mathematical model development is to find a way of computing the probability of a collision on a given hop as a function of time, to provide insights into the relationship between the number of frequencies, the number of users, and performance. Because the development in subsection II(B) is somewhat tedious, the resulting model is summarized in II(D) to allow the reader to skip II(B) without loss of continuity.

B. Model Development

The situation of interest here is inherently probabilistic in nature and so must be described statistically. In other words, the performance of a frequency-hopped cordless telephone should be characterized by such measures as the probability of getting hit on a given hop, the probability of receiving a given number of hits in a SF, the expected (average) number of hits per minute, etc. Such measures can be derived from the mathematical model developed here.

Consider a reference user on a given hop in the first SF. Since there is no hop-synchronization among users, all other users each have two hops that overlap the reference user's hop in time. Therefore, if there are a total of N frequencies available, the probability that a given user will hit the reference user on that hop is $2/N$. If there are K units operating (in addition to the reference user), the probability that none of them will hit the reference user on that hop is $(1-2/N)^K$. Hence, the probability that the reference user gets hit on that particular hop in the first SF is:

$$p_1 = 1 - \left(1 - \frac{2}{N}\right)^K , \tag{1}$$

where p_i will be used to denote the probability of getting hit on a given hop in the ith SF.[2]

Again, due to the lack of synchronization, each of the K units has two hops that overlap each hop of the reference user, so there are $2K$ hops that overlap that of the reference user (i.e., $2K$ opportunities for the reference user to get hit on each hop). For each of these $2K$ overlapping hops that gets hit in SF i-1, another frequency will be randomly selected for SF i. Let the random variable $\mathbf{k}_{i-1}$ represent the number of these $2K$ overlapping hops that get hit in SF i-1. The value of $\mathbf{k}_{i-1}$ is of interest because it determines the probability of the reference user being hit on the same hop in the next SF. To see this, assume that the hop was clear for the reference user in SF i-1, but k of the overlapping hops were hit and will therefore select new frequencies for SF i. The reference user therefore has k opportunities to get hit on this previously clear hop in SF i. That is, assuming that the random variable $\mathbf{k}_{i-1}$ takes on a specific value k, the probability that a hop that was clear in SF i-1 remains clear in SF i is:

2. If it is assumed that a given unit can choose the same frequency for both overlapping hops, then $p_1 = 1-(1-1/N)^{2K}$, which differs little from (1) for the range of N and K of interest here.

$$P_{CC,i\,|\,\mathbf{k}_{i-1}=k} = \left(1 - \frac{1}{N}\right)^{k}, \tag{2}$$

where $P_{CC,i}$ denotes the probability that a hop that was clear in SF i-1 stays clear in SF i.

Removal of the conditioning on $\mathbf{k}_{i-1}$ requires weighting by the probability density function (pdf) of $\mathbf{k}_{i-1}$ and summing over all of its possible values. Since the probability of any given overlapping hop getting hit on SF i is simply p_i, the probability that k of these $2K$ overlapping hops are hit is:

$$P\{\mathbf{k}_{i-1} = k\} = \binom{2K}{k} p_{i-1}^{k} \, (1 - p_{i-1})^{2K-k}, \tag{3}$$

where $\binom{2K}{k} = \frac{(2K)!}{(2K-k)!\,k!}$ is the number of possible combinations of $2K$ objects taken k at a time (or "$2K$ choose k").

Knowing $P\{\mathbf{k}_{i-1} = k\}$, $P_{CC,i}$ is:

$$P_{CC,i} = \sum_{k=0}^{2K} \left(1 - \frac{1}{N}\right)^{k} P\{\mathbf{k}_{i-1} = k\}$$

$$= \sum_{k=0}^{2K} \left(1 - \frac{1}{N}\right)^{k} \binom{2K}{k} p_{i-1}^{k} (1 - p_{i-1})^{2K-k}. \tag{4}$$

Since (4) is a binomial series, it can be expressed in closed form using the well-known relationship

$$\sum_{n=0}^{J} \binom{J}{n} a^n x^{J-n} = (a+x)^J . \tag{5}$$

Substituting $(1 - 1/N)p_{i\text{-}1}$ for a, $(1\text{-}p_{i\text{-}1})$ for x, and $2K$ for J in (5) allows $P_{CC,i}$ to be expressed as:

$$P_{CC,i} = \left[\left(1 - \frac{1}{N}\right) p_{i\text{-}1} + (1 - p_{i\text{-}1})\right]^{2K} = \left(1 - \frac{p_{i\text{-}1}}{N}\right)^{2K} . \tag{6}$$

This expression for $P_{CC,i}$ is consistent with intuition; the probability that a given one of the $2K$ overlapping hops will hit the reference user on SF i is $p_{i\text{-}1}/N$ (since the probability that a new frequency will be chosen for that overlapping hop is $p_{i\text{-}1}$ and given that it chooses a new frequency, the probability that it chooses the particular one occupied by the reference user is $1/N$). Thus, the probability that the given overlapping hop will *not* hit the reference user on SF i is $1 - p_{i\text{-}1}/N$, and the probability that *none* of the $2K$ overlapping hops will hit the reference user is $(1 - p_{i\text{-}1}/N)^{2K}$.

The next case that must be considered is one in which the reference user is hit on a given hop in SF i-1 and selects a new frequency for that hop in SF i. We need to know the probability that after doing so, the hop will be clear in SF i. At this point things get a bit more complicated, because some of the overlapping hops did not get hit in SF i-1, and will hold the same frequencies for SF i. If the reference user selects one of these frequencies, it will experience a collision with probability 1. If it selects one of the other frequencies (that are not held over) it can get hit by another overlapping hop that itself got hit in SF i-1 and is seeking a clear frequency.

Let the random variable $\mathbf{j}_{i\text{-}1}$ represent the number of overlapping hops that did *not* get hit in SF i-1. Note that $\mathbf{j}_{i\text{-}1} = 2K - \mathbf{k}_{i\text{-}1}$. If these $\mathbf{j}_{i\text{-}1}$ overlapping hops that did not get hit each occupy a different frequency, then $\mathbf{j}_{i\text{-}1}$ frequencies are held over to SF i. However, two different hoppers could use the same frequency on hops that overlap that of the reference user's, providing the hops do not overlap in time. Hence, the number of held-over frequencies can be expressed as $\mathbf{r}_{i\text{-}1}\mathbf{j}_{i\text{-}1}$, where $0.5 \leq \mathbf{r}_{i\text{-}1} \leq 1$. Clearly, $\mathbf{r}_{i\text{-}1}$ is a random variable, and its distribution depends on i and the value taken by $\mathbf{j}_{i\text{-}1}$, as well as the way in which the $\mathbf{j}_{i\text{-}1}$ overlapping "clear" hops are distributed between the beginning and the end of the reference user's frame.

If $\mathbf{j}_{i\text{-}1}$ and $\mathbf{r}_{i\text{-}1}$ take on some specific values j and r, respectively, then there are rj frequencies held over by previously clear hops. If the reference user chooses any of these frequencies in SF i, it will experience a collision. Hence, the probability that a hop (for the reference user) that was hit in SF i-1 is clear in SF i (because the reference user found a new, clear frequency for that hop) is:

$$P_{CH,i\,|\,\mathbf{j}_{i\text{-}1}=j,\mathbf{r}_{i\text{-}1}=r} = \left(1-\frac{rj}{N}\right)\left(1-\frac{1}{N}\right)^{2K-j}, \tag{7}$$

where $P_{CH,i}$ denotes the probability that a hop that was hit in SF i-1 is clear in SF i. The first term $(1-rj/N)$ is the probability that the user selects a frequency that was *not* held over on an overlapping hop that was clear in SF i-1. The second term $(1-1/N)^{2K-j}$ is the probability that the selected new frequency does not get hit by an overlapping hop that itself got hit in SF i-1 and has randomly selected a new frequency.

As before, finding $P_{CH,i}$ requires that the conditioning on $\mathbf{j}_{i\text{-}1}$ be removed by computing the pdf-weighted sum over all possible values of $\mathbf{j}_{i\text{-}1}$. Doing so gives:

$$P_{CH,i} = \sum_{j=0}^{2K}\binom{2K}{j}(1-p_{i-1})^j p_{i-1}^{2K-j}\left(1-\frac{rj}{N}\right)\left(1-\frac{1}{N}\right)^{2K-j}$$

$$= P_{CC,i} - \sum_{j=0}^{2K}\binom{2K}{j}(1-p_{i-1})^j p_{i-1}^{2K-j}\,\frac{rj}{N}\left(1-\frac{1}{N}\right)^{2K-j}$$

$$= P_{CC,i} - \alpha_{i-1}\sum_{j=0}^{2K}\binom{2K}{j}(1-p_{i-1})^j p_{i-1}^{2K-j}\,\frac{j}{N}\left(1-\frac{1}{N}\right)^{2K-j}, \tag{8}$$

where α_{i-1} represents the weighted-average effect of the term $\mathbf{r}_{i\text{-}1}$, and $0.5 \leq \alpha_{i-1} \leq 1$. The second